NASA TECHNICAL NOTE

NASA TN D-4785

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NASA TN D-4785

PRECISION FLOW MEASUREMENT TECHNIQUES FOR LOW-THRUST AUXILIARY-PROPULSION LIQUID ROCKETS

by Daniel J. Grant

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1969

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ABSTRACT

This paper concerns techniques for improving precision in measuring propellant consumption of small (0.5 to 5.0-lbf thrust) rocket engines. By proper use of impeller wheel meters for steady flow and a photometric device for pulsed flow, propellant flow and consumption data accuracies of better than 1 percent can be achieved. Flow-measurement requirements are considered for both steady and pulsed firing modes, for specific impulses of 150 to 350 seconds, and for oxidizer/fuel (O/F) ratios from 1 to 2. Frequency standards are used to correlate test-stand data with laboratory calibrations of impeller flowmeters. Fluid dynamic simulation is obtained by selecting inert fluids with kinematic viscosities approximately equal to those of the propellants. Anomalous behavior during calibrations indicate that normal turbine meter frequency-viscosity characteristics are not applicable to impeller-wheel units. The accuracy of the photometric device for pulsed-mode flow measurements depends on fluid meniscus displacement and can provide 99.7 percent probable range accuracy of $-0.423 \pm 3\ (0.999)$ percent for a 0.15-inch displacement and $+0.003 \pm 3\ (0.115)$ percent for a 1.75-inch displacement. The initial models are applicable to a thrust range of 1/2 to 25 lbf. Greater accuracy is feasible with commercially available components.

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INTRODUCTION

Spacecraft reaction control systems are selected in the initial planning and preliminary study stages of a program on the basis of mission study tradeoffs. Systems considered are those that have performed successfully in previous flights or those for which there are adequate, reliable performance data. Data are not acquired readily with standard instrumentation and techniques; therefore, it is necessary to develop the means by which system performance can be assessed in both the steady and pulsed modes of operation. Thrust and propellant consumption measurements are basic in defining engine performance. Accurate steady-state measurements are difficult, and the accurate measurement of transient performance is even more difficult because of the low sensitivity of high-frequency systems and the low-level signals associated with small thrusters.

This paper deals exclusively with the precise measurement of propellant flow rate, using commerical flowmeters for steady-state performance data, and propellant consumption, using instrumentation developed for pulsed-mode operation of Attitude Control System (ACS) thrusters.

The parameter ranges considered include thrust (0.5 to 5.0 lbf), specific impulse (150 to 350 seconds), and O/F ratio (from 1 to 2). Applications of these techniques for lower thrust levels are also indicated.

INSTRUMENTATION REQUIREMENTS

Propellant consumption data for the steady-state mode can be obtained by measuring either volumetric or gravimetric flow rate. Flow-rate measurements for the pulsed mode, however, introduce complications because they must be integrated to obtain propellant consumption on a "per pulse" basis, so as to establish the effective specific impulse as a function of the command duty cycle and fluid system dynamics. A second complication stems from interaction of the flow measuring device with the propulsion system, causing a change in the propellant feed pressures. In addition, to acquire specific impulse data to better than 2 percent accuracy, the accuracy of the propellant consumption data should be better than 1 percent and preferably closer to 1/2 percent.

Therefore, an instrument system that would provide a direct measure of average propellant consumption per pulse, and be passive relative to the feed system, was preferred.

Steady-Flow Requirements

The requirements for steady-flow instrumentation were established by considering the propellant properties, the thrust levels, the O/F ratios, and the specific impulse range for the earth-storable monopropellant and bipropellant systems. Propellants considered were hydrogen peroxide (90 percent), nitrogen tetroxide, neat hydrazine, and monomethyl hydrazine. Thrust levels were limited to 0.5 to 5.0 lbf. The O/F ratio range (where applicable) was arbitrarily fixed at 1.0 to 2.0. Specific impulse was varied from 100 to 240 lbf-seconds per lbm for the monopropellants, and from 250 to 350 lbf-seconds per lbm for the bipropellants.

Figure 1 is a plot of steady-state propellant flow rates, as a function of thrust and specific impulse, for the monopropellants. Figures 2(a) and 2(b) are plots of the steady-state flow rates, as functions of thrust and O/F ratios, for the monomethyl-hydrazine (MMH) and the nitrogen-tetroxide (NTO) bipropellant systems. The monopropellant flow ranges from 0.015 to 0.36 gallon per minute and the bipropellant systems vary from 0.004 to 0.0824 gallon per minute for

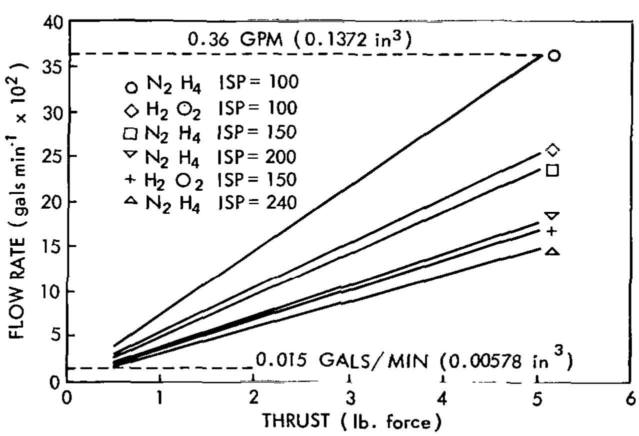

Figure 1—Monopropellant flow range.

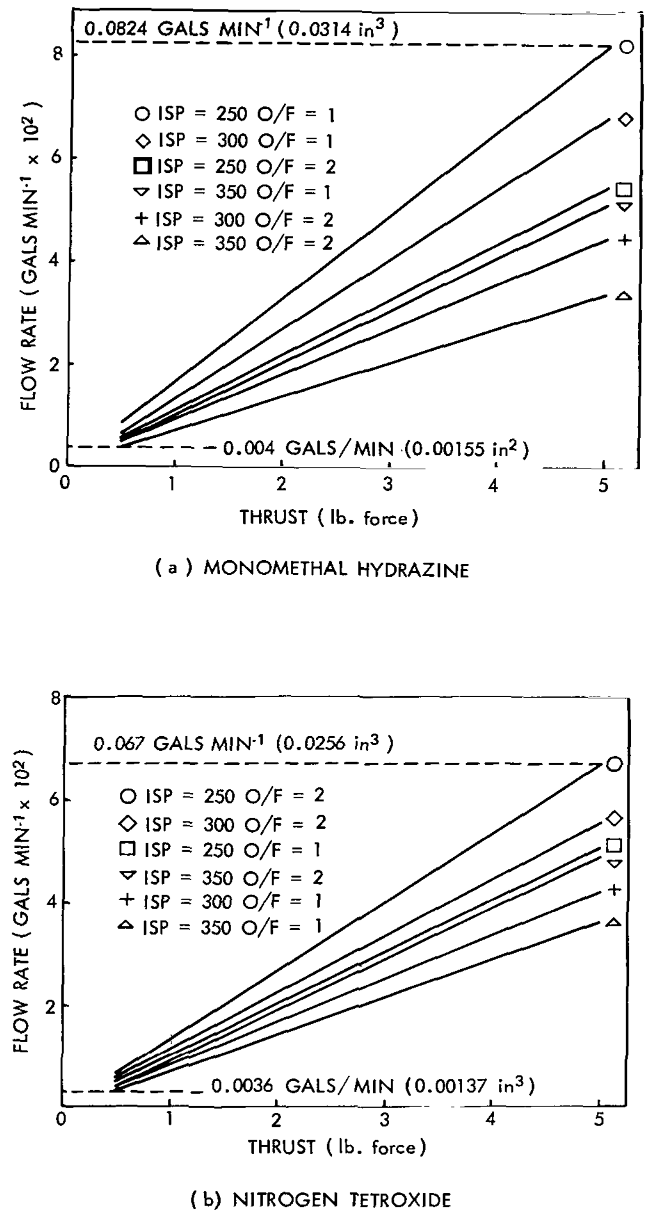

Figure 2—Bipropellant flow ranges.

MMH and from 0.0036 to 0.067 gallon per minute for NTO, over the complete thrust range. The overall range for all cases considered is 0.0036 to 0.36 gallon per minute.

Single-Pulse Propellant Consumption

In establishing the minimum requirement for measuring single-pulse propellant consumption for the same propellants as considered for the steady-state case, a pulse width of 100 milliseconds was selected as a baseline "on" time, since this value is in the range of command pulse widths for the class of ACS systems of particular interest. Single-pulse volumes (in cubic inches) can be obtained directly from the steady-state flow rates for both the monopropellant and bipropellant systems by multiplying the steady-flow gallons per minute by 0.385. Figures 1 and 2 indicate the upper and lower limits of volume for the 100-millisecond pulse in parentheses. The value shown for the steady state I_{sp} has its single-pulse, equivalent volumetric consumption indicated for an equal value of effective I_{sp} in the pulsed mode.

For the monopropellants, the lower and upper bounds for single-pulse consumption are 0.00578 cubic inch and 0.1372 cubic inch, respectively; the bipropellant lower and upper bounds for single-pulse consumption are 0.00137 cubic inch and 0.0314 cubic inch, respectively. These values can readily be converted to those required for longer or shorter pulses. The complete spectrum of indicated applications requires an overall range of 0.00137 to 0.137 cubic inch.

In both the steady and pulsed applications, the range spread is exactly 100 to 1. It is doubtful that any one instrument can cover the complete range with the desired precision for either firing mode. The normal range spread expected of flow devices is usually 10 to 1. Therefore, it will be necessary to use several instruments or to modify initial requirements such that propellant consumption is averaged over a train of pulses rather than a single pulse.

REVIEW OF EXISTING METHODS

A survey of commercial instrumentation, custom designs, and devices in use or under development was conducted. The factors considered in their evaluation were:

1. Sensitivity or resolution,
2. Ease of calibration with secondary standards,
3. Dependence of precision on fluid system dynamics,
4. Influence of human error,
5. Limitation of run time on test flexibility,
6. Linearity of output, where applicable,
7. Temperature effects on measurement precision.

Steady-Flow Measurements

Steady-flow rates have been measured successfully by the pressure drops across an orifice plate (Reference 1), the speed of the turbine meter (Reference 2), and by the force on a drag-body flow indicator (References 3 and 4). These devices are all purported to be accurate within 1 percent over a useful flow range of 10 to 1. The orifice plate, although accurate, is not particularly convenient to use, because of its poor response to fluctuations in steady flow; also, its output is not a linear function of the volumetric flow rate. Turbine meters do have adequate response and linearity characteristics, but they are not currently manufactured with sufficiently low flow ranges for the specified applications. Drag-body flowmeters have excellent dynamic response, but are nonlinear and do not cover the required flow range. In addition, their output depends on velocity distribution and (in some designs) upon a complex function of the fluid viscosity. These factors also contribute to the nonlinear output, which is inconvenient from an operational point of view.

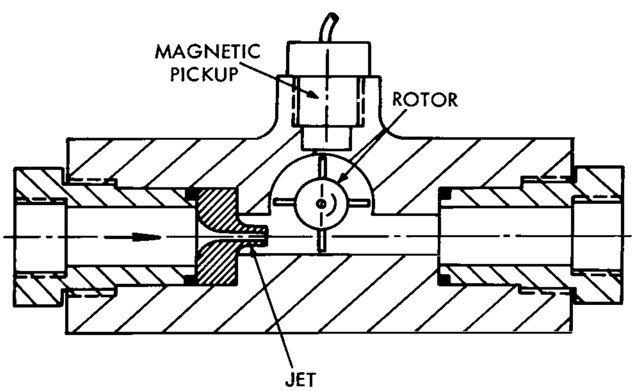

Figure 3—Cross-section of a typical impeller-wheel flowmeter.

The only commercially available devices that could be used for the indicated steady-flow ranges are impeller-wheel devices (Figure 3). These volumetric-type flowmeters generate an ac millivolt signal whose frequency is proportional to the flow rate. They differ from the standard turbine meter in that the rotor is supported by a shaft at right angles to the flow, rather than axially. The flow is directed by an orifice or nozzle perpendicular to the face of the rotor blade. Such devices, available as shelf items in nominal flow ranges as low as 0.005 to 0.075 gallon per minute, would cover all previously discussed low-range monopropellant-bipropellant requirements down to a thrust level of 0.75 lb force if they were usable for their entire range. Unfortunately, these units have not given a sufficiently stable signal at the lower one-third of their nominal range to permit calibration. In addition, a limited number of calibrations performed with deionized water and other inert fluids indicates that these devices are probably more sensitive to viscosity than turbine meters (Reference 5) and consequently would have a very limited linear range. Therefore, in order to use an inert calibration fluid, it would be necessary to match Reynolds number or kinematic viscosity to the corresponding number for the propellant as closely as possible. This will be discussed later in detail.

It has been suggested that flow rates can be obtained by photographing the propellant levels in glass dispensing tubes large enough to provide adequate sensitivity. This method is subject to displacement and timing errors caused by optical distortion and frame-rate variation. In addition, the data reduction process is more complicated than the more standard technique and could introduce additional errors.

Pulsed-Flow Measurements

A number of approaches used for measuring pulsed-mode propellant consumption were checked for adequate performance. The drag-body flowmeters described in Reference 3 are supposed to possess adequate response to measure pulsed flows. Yet, as shown in Figure 4, the device is generally calibrated in terms of total propellant mass per pulse as a function of normalized chart deflection for different pulse widths. For precision, the average flow for a number of pulses, rather than for the single pulse, is used. An analog computer integrates the area under the pulse flow trace; although the data system gain can be preset, there is no consideration of nonlinearities in the calibration process. The calibration curves for a pulse width range of 10 to 100 milliseconds are not colinear, and the spread between curves does not appear predictable. Integrated weight flows per pulse are repeatable within 1 percent. However, there are reasons why this device would not satisfy the requirements of a mass flowmeter having adequate dynamic response and accuracy for pulse operation—the relatively complicated process of calibration, data acquisition, and data reduction and the possibility of additional error caused by the nonlinearities of a fluid system highly dependent on fluid properties. The manner of calibration indicates that high transient response is not actually required. The basic need is an accurate indication of total integrated flow per pulse for a single pulse or average total integrated flow for a number of pulses. The chamber pressure and propellant feed pressure traces generally provide the transient data required to define the dynamics of the propellant systems.

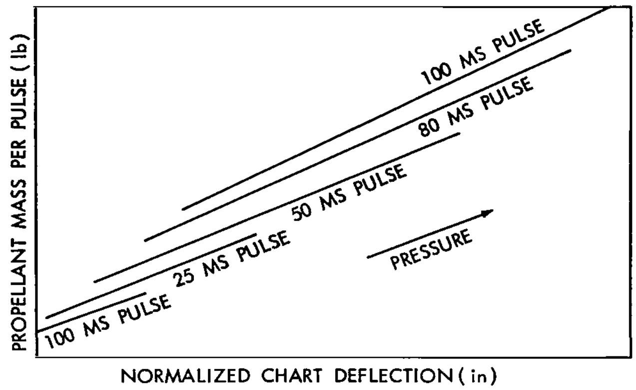

Figure 4—Typical drag-body flowmeter calibration.

The most commonly used devices are positive expulsion piston units, which appear in a wide variety of forms (References 6, 7, and 8), but are all designed to measure flow rate during pulse operation. They depend on a direct-coupled linear differential transformer or a linear potentiometer for a high-resolution analog output. The piston is driven by gas pressure, and the seal between the gas and the liquid sides is one of the various forms of dynamic piston seals or welded bellows arrangements. The bellows, when properly incorporated, prevent gas leakage and resulting errors that could occur with an O-ring failure or similar dynamic seal failure; but they can adversely affect the dynamic response of the unit and the linearity of the volumetric indication. Also, a "water hammer" effect can occur in the cutoff transient of the flow-rate trace. Therefore, the dynamic response of bellows, piston, and transducer to pressure waves during typical duty cycles must be considered in the basic design. Another complicating factor is that, in order to give the required resolution, all components must be specified stringently in terms of linearity, sensitivity, hysteresis, stability, response, life cycles, line regulation, load regulation, ripple voltage, etc.; also run times must be necessarily short. Therefore, there is needed some arrangement for rapid filling, or a multiplicity of units to alternately supply, and be supplied with, the propellants. To minimize the number of active components that must be carefully specified and to reduce the complexity of operation and calibration, a device that can develop the required resolution from common commercial components is needed. Also, measuring the propellant consumed by a multiple-pulse firing may develop the resolution.

The burette is a pulsed metering device that can be completely passive, involving no transient measurements, and can be tailored to provide a wide range of resolution with standard commercial components. With this device, inert gases directly pressurize the fluid contained in precision-bore tubes of metal or glass. The difference between the levels in the tube before and after firing a single pulse, or train of pulses, is a direct volumetric measure of the propellant consumed during the firing. The meniscus level can be monitored with a linear, differential transformer slug float, in the case of the metal tube, or an optical system in glass tubes. Metal units have obtained long run times by utilizing a multiplicity of coils along the tube axis and switching the electrical outputs as the slug float progresses from one coil to the next. Glass units have used light diffused through the liquid column and across the meniscus to drive a photoelectric tracking head to indicate position (Reference 9). Cathetometers, transits, or motion pictures have also been used to determine fluid level. A properly used cathetometer can permit reading the fluid displacement to within 0.002 inch; however, this depends on the skill of the operator. Tests of multi-operator variability have produced fixed-level data spreads of 0.020 inch—ten times the accuracy possible with the cathetometer. Photographic recording is slow and not reducible to the required accuracy or resolution.

An instrument with the inherent simplicity of a burette metering unit can give the required resolution. One that can eliminate sources of human error was considered the most suitable and was developed (Reference 10) in its simplest form. The synthesis, preliminary tests, and application of the unit will be described in detail under "Pulsed-Mode Flow Data Acquisition."

STEADY-STATE FLOW DATA ACQUISITION

As indicated earlier, impeller-type flowmeters are available that could cover all projected metering requirements for monopropellant thrusters and all bipropellant needs down to the 0.75-lbf thrust level. Two suppliers provided flowmeters—flowmeter "P" with a nominal range of 0.01 to 0.08 gpm and flowmeter "B" with a nominal range of 0.005 to 0.075 gallons per minute. The suppliers' calibrations were conducted with tap water and, in the case of P, appeared suspiciously linear over the complete flow range. It was, therefore, deemed necessary to check these calibrations and to consider deviations between water and propellant calibrations. Since the available facilities were not equipped to calibrate directly with propellants, inert simulants whose fluid properties closely model the kinematic viscosities, and therefore Reynolds numbers, of the propellants were selected. Fortunately, deionized water is an excellent simulant for hydrogen peroxide. Table 1 lists the properties pertinent to Reynolds-number simulation and additional fluid properties that can affect the performance of other flow metering devices. As indicated, suitable simulants are available for the hydrazine compounds, with Reynolds numbers being within 2.5 percent; but the closest inert simulant for nitrogen tetroxide comes to within only 10 percent of the kinematic viscosity.

Table 1

Physical Properties of Propellants and Simulants.

Fluid	Density (g/cc)	Dynamic Viscosity Centipoise	Kinematic Viscosity Centistoke	Refractive Index Sodium D	Surface Tension (dynes/cm)
Nitrogen tetroxide	1.434 (25°C)[c]	0.4130[a]	0.2880	1.400 (20°C)	28.00
Methylene chloride	1.336	0.4137[d]	0.3097	1.4237 (25°)	26.52 (20°)[d]
45.7% Sodium dichromate	1.2378[e]	—	—	1.400[e]	—
MMH	0.877[a]	0.85[a]	0.9692	1.4218	—
Deionized water	0.9968[b]	0.8937[b]	0.8965	1.3325	71.97 (25°)[d]
Glycerol sol. (20%)	1.0469 (20°C)[b]	—	—	1.4218	68.00 (18°)
N_2H_4	1.006[a]	0.97[a]	0.964	1.470 (22°)[d]	66.67 (25°)
Silicone blend (A)	0.818[e]	0.773[e]	0.945	1.3818	15.90
H_2O_2 (90%)	1.390 (20°C)[a]	1.26[a]	0.906	1.399 (22°)	76.1[d]

References:

a. The Handling and Storage of Liquid Propellants, D.O.D. Off. of the Director of Def. Res. & Eng. 1965.
b. Perry's Chemical Engineers Handbook McGraw-Hill, 4th Ed. 1963.
c. Gmelins Handbuch der Anorganischen Chemie Verlag Chemie, 8th Ed. 1955.
d. International Critical Tables of Numerical Data, Physics, Chemistry and Technology, McGraw-Hill, 1st Ed. 1928.
e. GSFC Propellant Chemistry Laboratory Measurements.

Careful consideration of calibration, data acquisition, and data reduction processes indicated that one possible, serious source of error existed: discrepancies between data taken at the test stand and data taken in the calibration laboratory. The commercial flowmeters each produce an ac signal whose frequency depends directly on impeller speed. The ac signal is converted to a dc output by a frequency converter; this output provides an analog record. A secondary check of the analog rates can be made by means of the digital totalizer output and elapsed time indicators.

A simple, direct procedure was established to correlate test stand and laboratory calibrations. At the test stand, the frequency converter is calibrated with an oscillator and an electronic counter The output is recorded on a Visicorder, with the amplitude adjusted to provide a 4-inch deflection at 800 Hz for impellers that produce eight impulses per revolution and the same deflection at 200 Hz for impellers that produce two impulses per revolution. For applications where the flow range is in the lower one-third of the meter's nominal range, the amplification is increased so that greater data reduction precision is possible at very low flows. The converter is calibrated again in the laboratory with the same or a similar oscillator (checked by an electronic counter). This procedure provides the direct correlation between test stand and laboratory instrumentation and should compensate for differences in response and linearity. It is now possible to perform the flow calibration in which the flow in pounds per second is measured against the recorder deflection by the gravimetric-collection method. The precision platform balance used for this purpose can be read directly to 0.01 pound and estimated to 0.005 pound; a megahertz electronic counter provides more than adequate timing precision. The sample is collected until the maximum possible weighing error is 0.1 percent of the total weight, that is, until approximately 5 pounds is collected. The fluid whose properties closely simulate the propellant of interest is used, and its temperature is measured at the flowmeter, so that volumetric flow rate can be plotted accurately. The laboratory volumetric calibration and the test stand analog records of propellant temperature and volumetric flow rate are then used to compute the mass flow rate during engine firings.

Figures 5 and 6 are block diagrams of the instrumentation used for this work. Figure 5 shows the test stand frequency calibration equipment; Figure 6 shows the laboratory equipment. The electronic timer in Figure 6 is started (in the timing mode) by the fluid interrupting a beam of light in a photoelectric head, and is stopped by the scale pointer reducing the illumination to a second

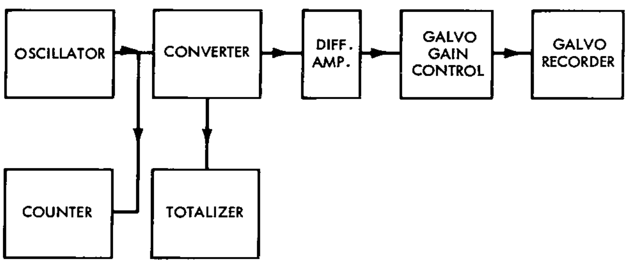

Figure 5—Test stand frequency calibration.

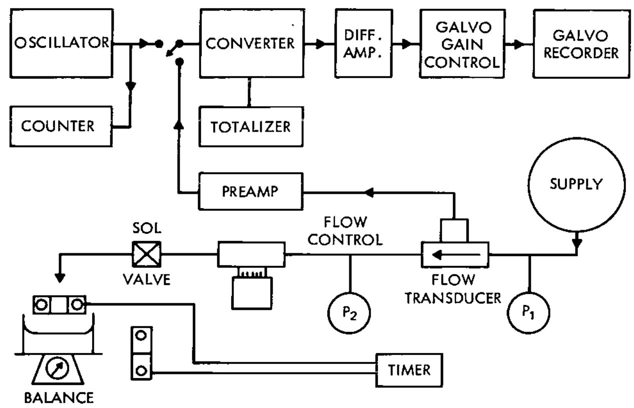

Figure 6—Instrumentation for steady-flow calibration.

photoelectric head on the scale. The "dribble" volume of the system is minimized by close-coupling the control solenoid valve to the "start" head. The scale is rebalanced and read after the counter time interval is recorded. Figure 7 shows a typical flow calibration record. The broken line indicates how this calibration would be used to reduce test stand data. The volumetric flow rate obtained would have to be converted to a mass flow rate at the temperature of the propellants at the test stand. Figure 8 is a photograph of one of the laboratory flow calibration benches showing all equipment and instrumentation.

Fluid properties are an important consideration in selecting the calibration fluid, as shown by plotting volumetric flow rates for deionized water and methylene chloride versus frequency for supplier P's meter (Figure 9) and supplier B's meter (Figure 10). The manufacturer's water calibrations were plotted on the same graphs.

Examination of Figure 9 indicates a performance paralleling that of the more conventional turbine meter: for a given volumetric flow rate, a lower viscosity fluid produces a higher frequency. The supplier's water calibration does not bear this out. In fact, at the linear portion, its frequency is 12 percent higher than that of the GSFC water calibration. The variation of the water calibration from the methylene chloride is approximately 4.5 percent for the same range.

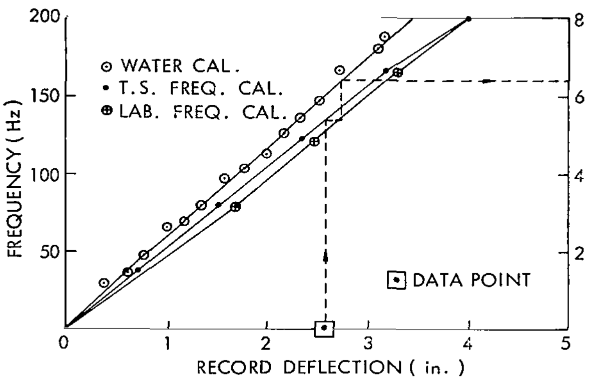

Figure 7—Typical flowmeter calibration record.

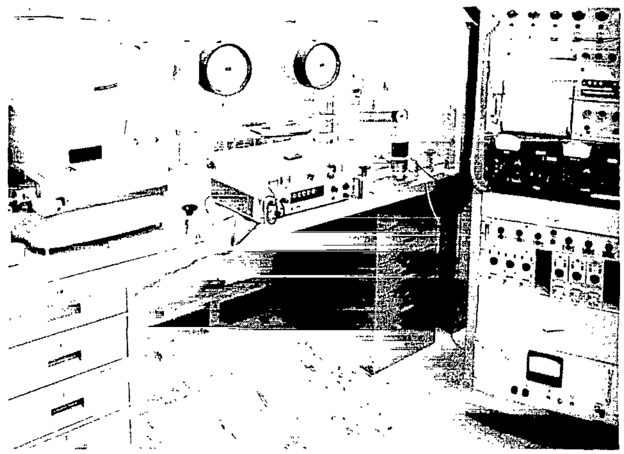

Figure 8—Flow calibration bench.

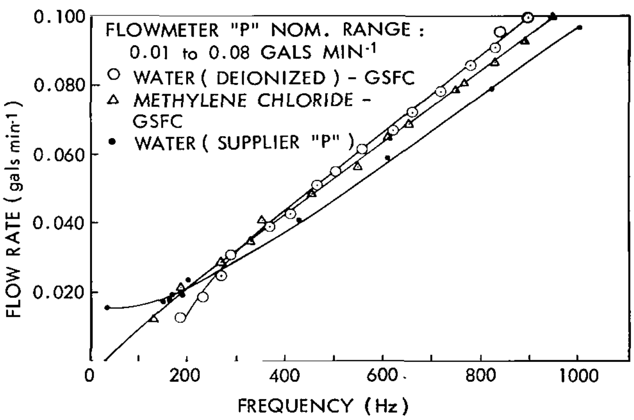

Figure 9—Meter "P" flow calibrations.

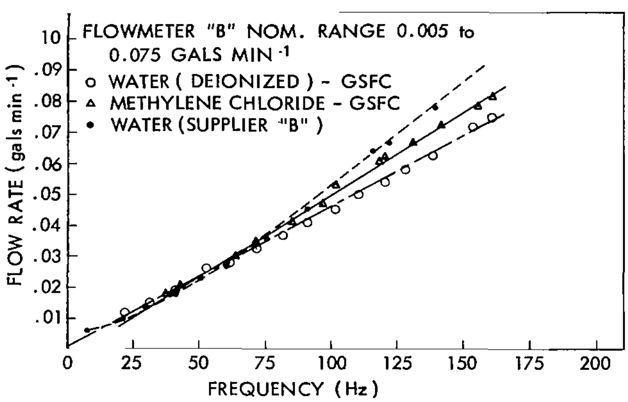

Figure 10—Meter "B" flow calibrations.

Comparison of the water calibrations for flowmeter "B" (Figure 10) shows that the supplier's frequency output data in the linear range are approximately 25 percent lower than the GSFC data. The GSFC water calibration has approximately 20 percent higher frequency output than the methylene chloride. This is contrary to what is normally expected since the higher viscosity fluid usually provides a lower frequency output. No reasonable explanation for this has as yet been evolved. If water calibration data were used for an MMH run, the volumetric flow rate, theoretically, would be 20 percent higher than the measured runs, thereby producing an equivalent error in the specific impulse data. Although the behavior of meter "B" is not what would normally be expected, repeated calibrations have shown better reproducibility than has been obtainable with the more conventional meter "P."

Since these meters are volumetric-flow devices, it would reduce human error to measure volumetric flow directly rather than to measure gravimetric flow. This would permit correlating calibrations of flowmeters with real propellants while reducing the hazards, since the fluids need not be collected to obtain the desired accuracy (they could be dumped into neutralizers or collected cryogenically).

When these correlation data become available, it will be possible to demonstrate whether simulating a propellant with a fluid having a comparable kinematic viscosity can replace the more hazardous propellant calibration in these low-range flowmeters. The same data may explain the varying behavior of similar meters. Progress to date in this area demonstrates two important requirements:

1. The choice and use of simulants, as shown by their varying and anomalous performances with different devices, and
2. Basic theoretical studies of the behavior of low-flow-rate impeller-wheel meters.

PULSED-MODE FLOW DATA ACQUISITION

The following paragraphs describe the development, limited testing, and application of a burette metering unit designed to eliminate most human error sources and provide accuracies of 1 percent or better for volumetric displacements of approximately 1/2 milliliter. The developmental model is a remote-controlled device which can be charged, pressurized, and zeroed from a manual control panel. It dispenses propellant at the remote test stand and provides precision readouts at the panel. The unit can be modified for automatic tracking of the fluid levels to provide a comparable accurate rate signal.

The manually operated pulse-mode flowmeter consists of two precision-bore glass tubes, sealed to a common pressure manifold at their upper ends and to solenoid valves terminating at a propellant manifold at their lower ends. Each glass tube is encircled by a photohead driven along the tube by a ball-screw assembly and motorized lead screw. The photohead contains a point light source and photodiode. The meniscus of the liquid in the tube can be detected by the change of the diode output. Precise resolution of the fluid level is achieved by initially nulling the photodiode outputs, The change in fluid level is digitized by bidirectional pulse generators directly coupled to the lead screws. The pulse counter readout directly indicates meniscus travel in 0.001-inch increments. Figure 11 is a photograph of the burette unit with its steel cover removed. The limit switches shown prevent the optical heads from being driven into the upper and lower manifolds. The intermediate limit switches

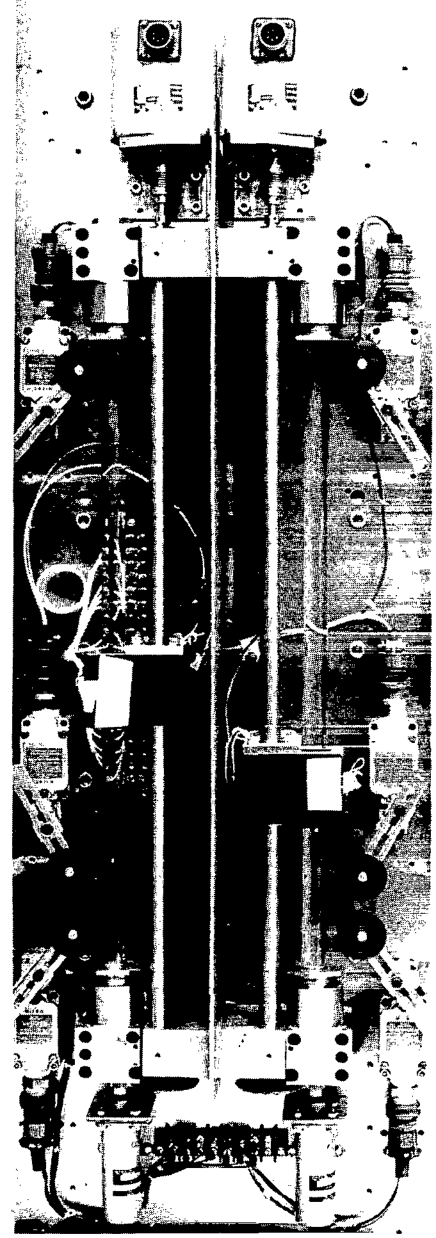

Figure 11—Development model of pulsed-model flowmeter.

provide a signal at the control panel to indicate when the heads are 1 inch from the lower limit switches, so that the tubes can be recharged before complete rundown. Figure 12 is a photograph of a control panel for a bipropellant system, which incorporates fuel and oxidizer controls. It shows the null indicator, control switches for motor drives, light (null indicator) intensity adjustment, and diode bias control.

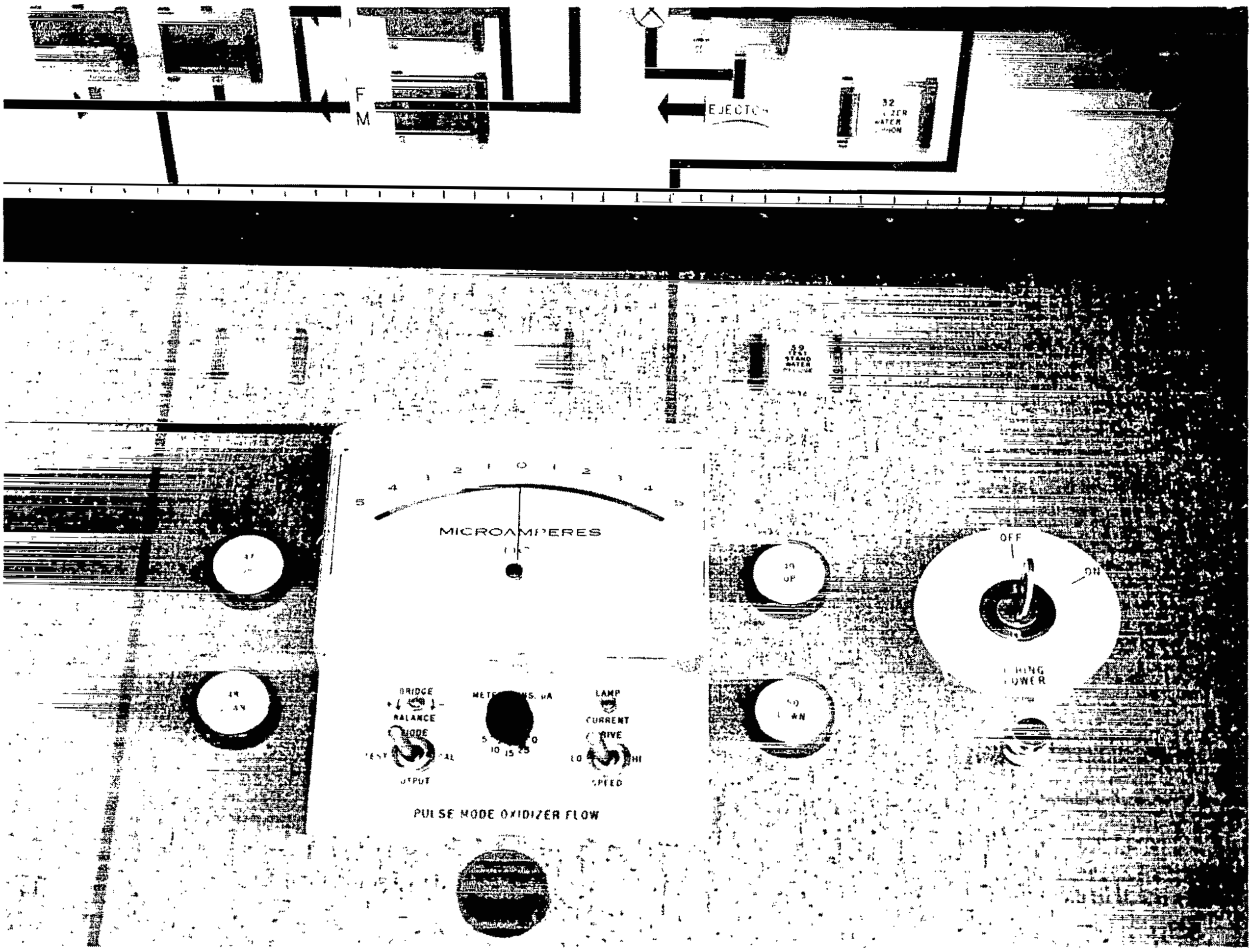

Figure 12—Control panel for pulsed-mode flowmeter.

Initial Sizing of the System

The selection of geometric and electrical parameters was simplified by testing available photodiodes (1N2175) for their ability to indicate small liquid-level displacements. The first test used a single light source; the diodes were wired as two legs in a Wheatstone bridge, with potentiometers in the other two legs. The units were nulled across a galvanometer by longitudinally displacing glass tubes, partially filled with water, clamped into a supporting fixture. Since one of the glass tubes was fixed relative to the base, displacement of the fixture unbalanced the bridge. The galvanometer was used to return the fixture to a null position, and the fixture position was read with a dial indicator to 0.0001 inch. Sixty readings were taken and the null position averaged. The standard deviation computed for the variance about the mean position was 0.0001 inch. To determine the sensitivity for a null arrangement using two separate light sources, an additional 66 readings were taken; the standard deviation from the mean position was 0.0002 inch. Therefore, if a maximum position error of 0.001 inch were tolerated, the photodiode bridge would be at least five times more sensitive than required to sense a displacement within the selected tolerance.

Since initial programs were concerned with 5-lbf bipropellant systems, the first developmental models were sized for use with these items. Computations were performed to establish maximum overall measuring accuracy assuming that a total equivalent error of 0.001-inch travel could be tolerated. These computations were based on a 100-millisecond pulse width and a 0.500-inch bore tube in the burette. At the 5-lbf thrust level, for an I_{sp} range of 250 to 350, an O/F range of 1.0 to 2.0, and the number of pulses equal to 5, the theoretical accuracy was 0.28 percent, with a fluid column range of 0.352 to 0.808 inch. The same conditions with 10 pulses provided an accuracy of better than 0.7 percent for a thrust of 1 lb. Using the same geometry, it is theoretically possible to achieve accuracies better than 0.34 percent (with a 0.001-inch tolerable error) for monopropellants (H_2O_2, N_2H_4) throughout the 1- to 5-lbf thrust levels. If the tolerable equivalent linear error is reduced to 0.0005, the accuracies will improve by a factor of 2. To use the same geometry for shorter pulse lengths, it would be necessary to increase the number of pulses to be fired before a reading is taken, the increase being in direct proportion to the ratio of the standard pulse width (100 ms) to the varied pulse width. The usable burette tube length was determined by the mean displacement of oxidizer and fuel for optimum performance of a 5-lbf engine, or approximately 15 inches for 150 pulses. To make the tubes much longer produces an unwieldy, excessively heavy package and makes inspection of tube bores difficult.

To use the apparatus for the lower end of the scale (0.5-lbf thrust), a second set of precision bore tubes is contemplated. If the cross-sectional area is one-tenth that of the first set, equal theoretical accuracy will be experienced for the same number of pulses as that described above the 5-lbf level.

At the other end of the spectrum, a 25-lbf engine would meet the measuring accuracies quoted for the 5-lbf engine when only one pulse is fired, and in each leg the unit would supply sufficient propellant to fire 30 pulses; that is, a total of 60, 100-millisecond pulses before recharging would be necessary. Since the possibility of work at this level is not unreasonable, the current equipment, when properly applied, is theoretically capable of 0.25-percent accuracy over the thrust range of 0.5 to 25.0 lb, or a range of 1 to 50.

System Error Analysis

In selecting standard commercial components that could achieve the theoretical accuracy, it was necessary to consider the effects of tolerance variations of critical components. The items of primary concern were variations of bore diameter, lead screw error, pulse generator phasing, and counter stability. Other factors to be considered were varying indices of refraction, diode mismatch, varying light source intensities, and pressurization gas solubility effects on fluid density.

Tube-Area and Lead-Screw Errors

Assuming a nominal diameter D = 0.500 inch and diameter errors of 0.0001 inch and 0.001 inch gives area errors of 0.04 and 4.0 percent, respectively. Lead screws are standard items with pitch errors of 0.0015 inch in 1.000 inch or 0.0005 inch in 12 inches. The first error is equivalent to 0.15 percent (assuming distributed error), and the second is equivalent to 0.0042 percent.

To obtain the combination of the most precise bore and the better lead screw, a 0.044-percent volumetric error is the best that can be expected (assuming that temperature variations at laboratory and test stand are kept to within ±2°F). Considering the worst combination of lead screw and tube, the best accuracy that can be expected is 0.55 percent on volume alone. The most precise bore and lesser lead screw combination produces a 0.19 percent volumetric error.

Pulse Generator and Counter Errors

The errors in the bidirectional pulse caused by generator are inaccuracies in phasing the grating slots and cumulative effects in any sector of the grating. It is not sufficient to obtain 200 counts in 360 degrees if the lead screw has a 0.200 pitch. Not only should each count be ideally within 10 minutes of its true phasing, but any accumulated count within 360 degrees of rotation should be less than 10 minutes in error. This means that, if on one count the error is +6 minutes, the succeeding counts must not exceed by 4 minutes or be lower by -16 minutes. In general, phase errors will accumulate in a random fashion, and the cumulative effects should be checked out for 360 degrees in both directions. If a 2000-count generator is used (to obtain better measuring resolution), then the maximum individual and cumulative phase error in either direction should be 1 minute.

Optical System Sensitivity

The optical heads (which in essence form a balanced photometer circuit) consist of two 1N2175 photodiodes illuminated by individual 253X miniature high-intensity focused beams. Two 4700-ohm potentiometers make up the other side of a Wheatstone bridge that is excited by 45 vdc. The bridge output is sensed by a 5-0-5 microammeter with a series of shunting resistances to reduce sensitivity. An on-off switch in one of the diode legs permits the production of a fixed photocurrent level in the diode by light-intensity adjustment. This is done while the beam is completely in the liquid, in order to obtain a fixed output for liquids of varying transmissibility. With the diode switch completing the circuit, the light source in the opposite head is adjusted to provide a null condition (both heads in fluid). This compensates for deviations in light sources and in diode characteristics. A second, finer nulling procedure at the meniscus readies the instrument for data taking.

The only other effect that might possibly cause deviations in performance is the variation in refractive index of the liquids. A series of tests on the simulants whose optical properties matched those of the propellants was conducted to establish the seriousness of this variable.

Gas Solubility Errors

Since this device does not separate the gas from the liquid interface, it is reasonable, especially at high feed pressures, to expect solution of the nitrogen gas in the simulants and in the actual propellants. From available experimental data (References 11 and 12), estimates were made of the change in density of the propellants and simulants for a temperature of 68°F and a pressure of 200 psia. The nitrogen tetroxide under these conditions dissolves enough gas to give a 5.8-percent density increase. Monomethyl hydrazine, under the same conditions, would give less than a 0.2-percent change. Water has approximately a 1.1-percent density change. Methylene chloride effects were based on carbon tetrachloride data and estimated to have a 5-percent density increase caused by nitrogen solution.

The effect of gas solution can present a far greater error in measurement than all other factors previously considered. It can also affect the computation of measured performance, unless carefully assessed. Fortunately, the density change of the basic bipropellants and their simulants because of nitrogen solubility is within 1 percent, so that the kinematic viscosities will still have a reasonably good match. To overcome these difficulties, in view of the scarcity of data, it will be necessary to acquire experimentally all information not available in the literature and to spot-check that which is available.

Laboratory Tests and Evaluations

The testing performed to date was initially intended to check the precision of the primary components, and then to check system performance. Whenever possible, a large number of readings were taken at any set point to provide a more acceptable basis for statistical analysis of the data. In these cases, the mean and standard deviations from the mean were computed, and the error spread presented as the mean ±3 standard deviations to include all possible data points with a 99.7 percent probability (Reference 13). The system tests were conducted with water and with the 45.7-percent sodium dichromate solutions having indices-of-refraction of 1.3325 and 1.400, respectively. In both cases, nominal fluid column displacements of 0.15, 1.00, and 1.75 inches were run; volumetric error was computed from a gravimetric measurement of the fluid dispensed. The tests were conducted (as shown in Figure 13) at a 30-psig nitrogen-liquid interface. Samples were collected in glass vials by means of a pulsed solenoid valve and weighed with a Right-a-Weigh digital balance that is accurate to 0.1 milligram and reproducible to better than 0.02 milligram. The following paragraphs summarize the results of the initial performance tests on the development model.

Pulse Generator and Counter Accuracy

The pulse generator and counter subsystem were checked for phase error at indicated count and for cumulative phase error throughout the generator's entire 360-degree range by means of an

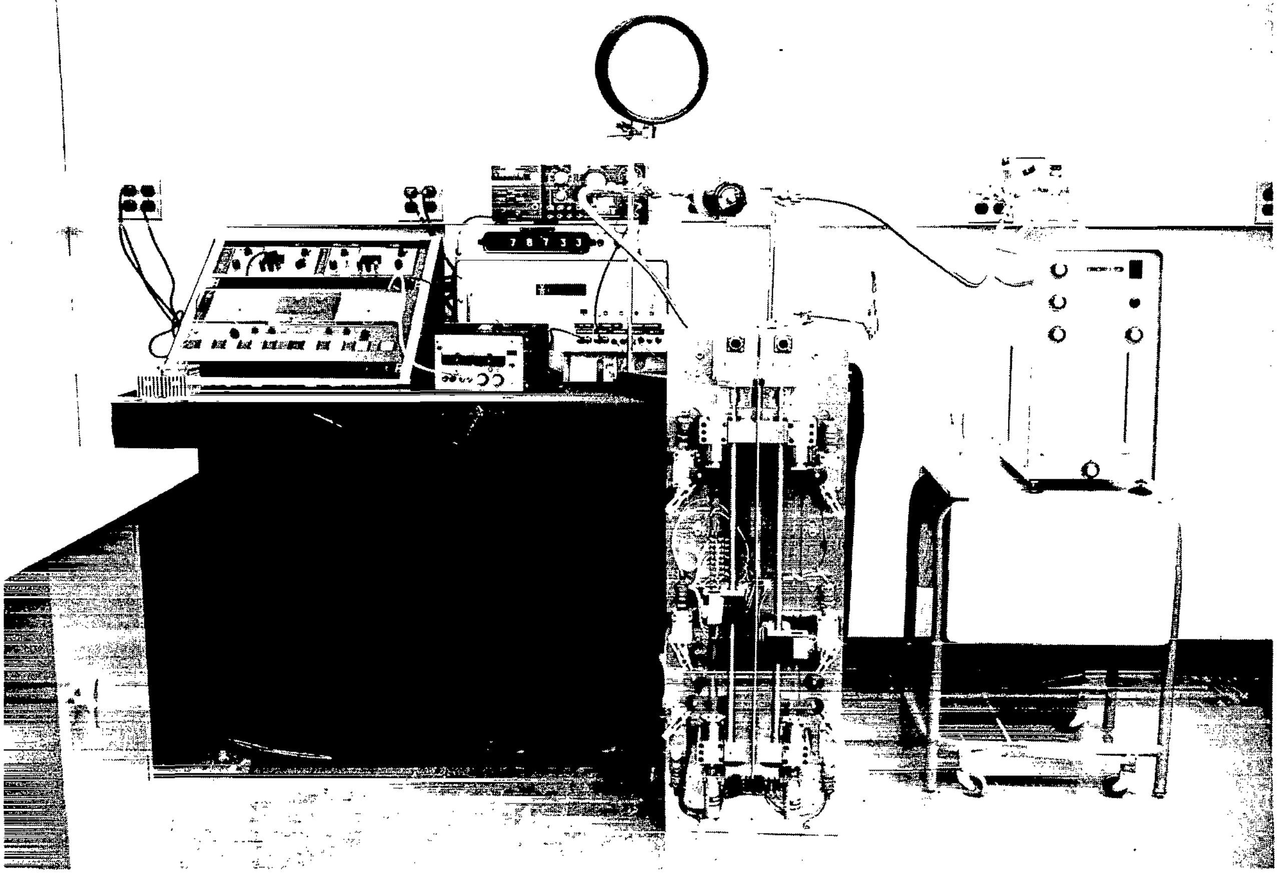

Figure 13—Laboratory calibration of pulsed-mode flowmeter.

optical master dividing head with a working accuracy of ±2 seconds of arc. The generator shaft was rotated slowly until a count was indicated on the digital readout. The optical dividing head setting was then noted. For the 200-pulse/360-degree units, each count is supposed to represent 1.8000 degrees of arc, or a linear travel of 0.0010 inch. The maximum individual deviation on count phase was found to be 0.039 degree (2.34 minutes), which is equivalent to a tracking error of 22 microinches. The maximum accumulated deviation occurred 103 degrees away from the maximum individual deviation and was 0.338 degree (20.2 minutes), which is approximately twice that of an ideal system. However, this represents a tracking error of 0.0002 inch, which is still well within a single-count resolution and is close to the photohead resolution limit. During tests, and for an additional 8 hours in which the counter was left running with the pulse generator stationary, there was no count instability.

Lead-Screw Error

Sixty positions along the 14.25-inch active length of the rolled thread lead screw were checked by a universal measuring machine having 0.0002-inch graduations and a 0.00002-inch vernier. The difference between counter reading and bed position was considered to be the lead-screw pitch error at the bed position. Between stations 10.750 and 14.250, the errors fluctuated consistently above the specified tolerance of 0.0015 inch/inch. Deviations of as much as 0.002 inch in 0.250 inch occurred in the last usable half inch. However, if this last section is avoided, and 1-inch increments of travel are used, the lead screw error will still be within 0.1 percent. Final models of the burette system should be made with the precision lead screw (0.0005 inch/12 inches) so that there can be unqualified operation of the device.

Bore Tests

The bore was checked at quarter-inch intervals along 7 inches from each end. The mean bore and tolerance was found to be 0.5002 ± 0.0001 inch, which is well within the limits set for a high-quality unit. In addition to the dimensional checks, three units successfully stood a pressure test at 525 psia. The design loading is 300 psia.

The combination of tube, lead screw, and digital system (avoiding the last measured half inch of screw) will allow a maximum theoretical volumetric error of 0.20 percent.

Laboratory Tests with Simulants

The complete system tests were conducted at nominal column heights of 0.15 inch, 1.0 inch, and 1.75 inch, first with deionized water and then with 45.7-percent sodium dichromate solution. Both systems were pressurized to only 30 psia, to reduce the solubility errors to where they could be neglected. Table 2 is a tabulation of the results of these tests based upon gravimetric collection. Because the nominal length could not be exactly controlled for each data point, individual trial error was expressed as a percentage of the true column height. The mean error is therefore also expressed as percentage of nominal tracking length along the burette column. The standard deviation is a measure of the variance of the sampled data. The mean error $\pm 3\sigma$ would provide the most pessimistic picture of system capability and would include 99.7 percent of all probable error caused by equipment and personnel. These figures show that, in general, as the column length

Table 2

Results of Complete System Tests.

Fluid	No. Trials	Nominal ΔL (inches)	Mean Error $\bar{x}$ - %	Standard Deviation σ - %	99.7% Probable Range	
					$\bar{x} + 3\sigma$	$\bar{x} - 3\sigma$
Deionized water N_D = 1.3325	50	0.15	-0.423	0.999	+2.574	-3.420
	44	1.00	-0.089	0.212	+0.547	-0.725
	25	1.75	+0.003	0.115	+0.348	-0.342
45.7% Sodium dichromate N_D = 1.400	54	0.15	-0.047	0.900	+2.653	-2.747
	47	1.00	-0.248	0.239	+0.469	-0.965
	38	1.75	-0.074	0.134	+0.328	-0.476

increases, the error drops off. For a displacement of 0.15 inch, the accuracy is -0.423 ± 3 (0.999) percent; for a displacement of 1.75 inch, the accuracy is +0.003 ± 3 (0.115) percent. The most significant result of these tests is that the index of refraction, N_D, over the range of interest does not materially affect the measurement accuracy.

Initial Application

One of the two developmental units was used to obtain the pulsed-mode performance of a 0.5-lbf thrust monopropellant hydrazine engine. The total propellant consumptions for trains of 50 pulses were measured, with command pulse widths varying from 100 to 500 milliseconds. Additional tests were conducted in which a low-range (0.005 to 0.075 gallon per minute) impeller-wheel flowmeter was coupled in series with, but downstream of, the photometric unit. This was done to check the validity of data obtained from turbine type devices. Figure 14 shows oscillographic tracings, which demonstrate the mutual effects of the meter and engine dynamics. The top trace is the chamber pressure with the impeller meter just upstream of the engine; the middle trace is the impeller-meter output; the bottom trace is the chamber pressure with the impeller meter out of the fluid circuit. These traces indicate several interesting phenomena. The peak-to-peak amplitude of the chamber pressure variation is 8 percent for the lower trace, and 15 percent (or approximately doubled) for the upper trace. In addition, the *mean* amplitude pressure rise is linear with time for the lower trace, while the pulse pressure *mean* for the upper trace oscillates about a linear rate line. The flowmeter trace indicates that the response of the meter is definitely inadequate. Steady-state flow conditions are not attained during the relatively steady portions of the pressure pulse. The peak values of the flow rate fluctuate, and the tailoff never achieves a zero value. Figure 15 is a tracing of the meter output for the first, second, third, and seventh pulses for a 50 percent command duty cycle having a 1-second period. It is obvious that, even for relatively long pulse operation, the impeller inertia makes this unit unsuitable for this test. The peak frequency of the first pulse overshoots that of a stable pulse (i.e., number 7) by 50 percent. The tailoff frequency never drops below 20 percent of the steady-state portion of the stable pulse. The record could not be used for normal data

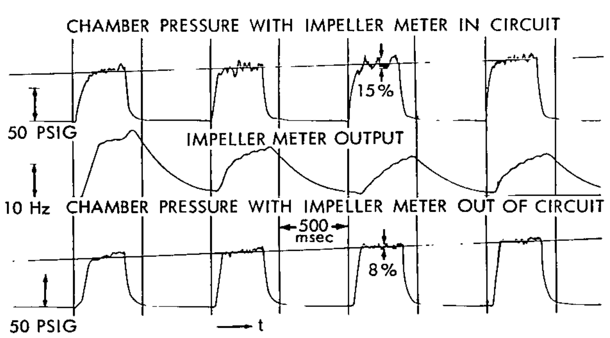

Figure 14—Sea-level firing—0.5-lbf thruster (30-percent duty cycle).

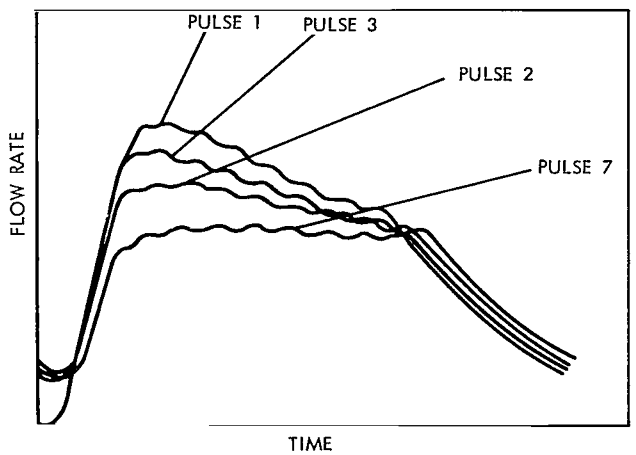

Figure 15—Impeller flowmeter output in pulsed application.

reduction. It can be seen that using meters of this type can influence combustion-chamber dynamics and using a burette-type device enables the acquisition of propellant consumption data without exerting as much influence on engine performance. This entire area of small-engine testing deserves more attention and should be investigated more thoroughly. It should be noted that this device reduces the feed system coupling to the reactor but does not simulate the transient associated with ACS propellant distribution systems, as it is designed for component test use. In order to assess complete system effects, feed system transients would have to be superimposed.

SUMMARY AND ADDITIONAL WORK

Although techniques have been developed to permit useful applications of existing steady-flow impeller devices, it is felt that their behavior has not been studied sufficiently either by manufacturers or by GSFC to prove that they perform reliably or with high precision. It is necessary to perform frequent calibrations to check performance reproducibility. Much fundamental work will be required to ascertain the basic behavior of impeller flowmeters and to learn why similar devices from different manufacturers do not respond similarly to viscosity changes. Performance must be characterized in a general way in terms of viscosity, flow rates, and impeller speed. Criteria for performance should be sought to synthesize more reliable and durable units.

To accomplish the above, it will be necessary to develop precision volumetric-flow calibration techniques that maintain the high feed pressures of test-stand propellant systems. These same volumetric calibration devices will also permit direct checkout with propellants to provide data to validate the use of simulants for routine calibrations. Recent work has shown (References 14, 15, 16, 17) that errors incurred by pressurization gas solubility are not as severe as originally indicated, and are in fact an order of magnitude lower. Therefore for the pressure ranges of interest, this factor can be neglected.

Work to date on the photometric pulsed-mode flowmeter with operational units has shown that reasonably good performance can be realized over a fairly wide thrust range (1/2 to 25 lbf) if normal care is exercised. The device is fairly foolproof and can indicate leakage or other operational difficulties because of its high tracking sensitivity. The current manual model is being redesigned to provide a cleaner, lighter unit with an additional digit in the counter so that the accuracy can be doubled by reducing the current ±0.001-inch error limit to ±0.0005 inch or better. A precision lead screw will be used in place of the current rolled-thread screw, to provide more precise tracking, and a servo-driven unit is being considered for engineering and operational feasibility. It is believed that such a unit could closely approach the tracking precision of a manual device.

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, January 23, 1968
731-13-02-98-51

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